Multilayer mirrors for Free Electron Laser Applications

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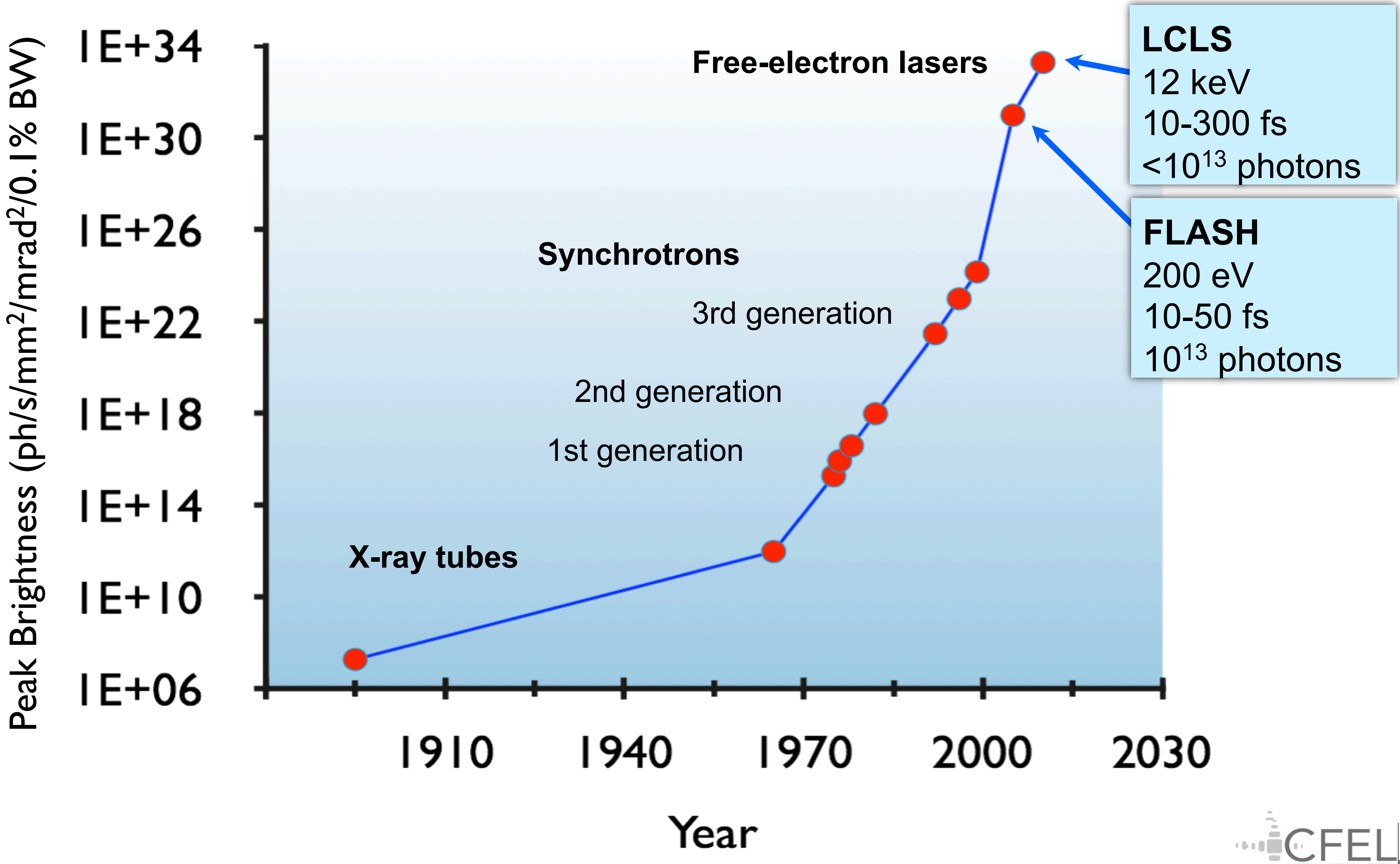
2011 International Workshop on EUV and Soft X-ray Source, November 7-10, 2011, Dublin, Ireland land

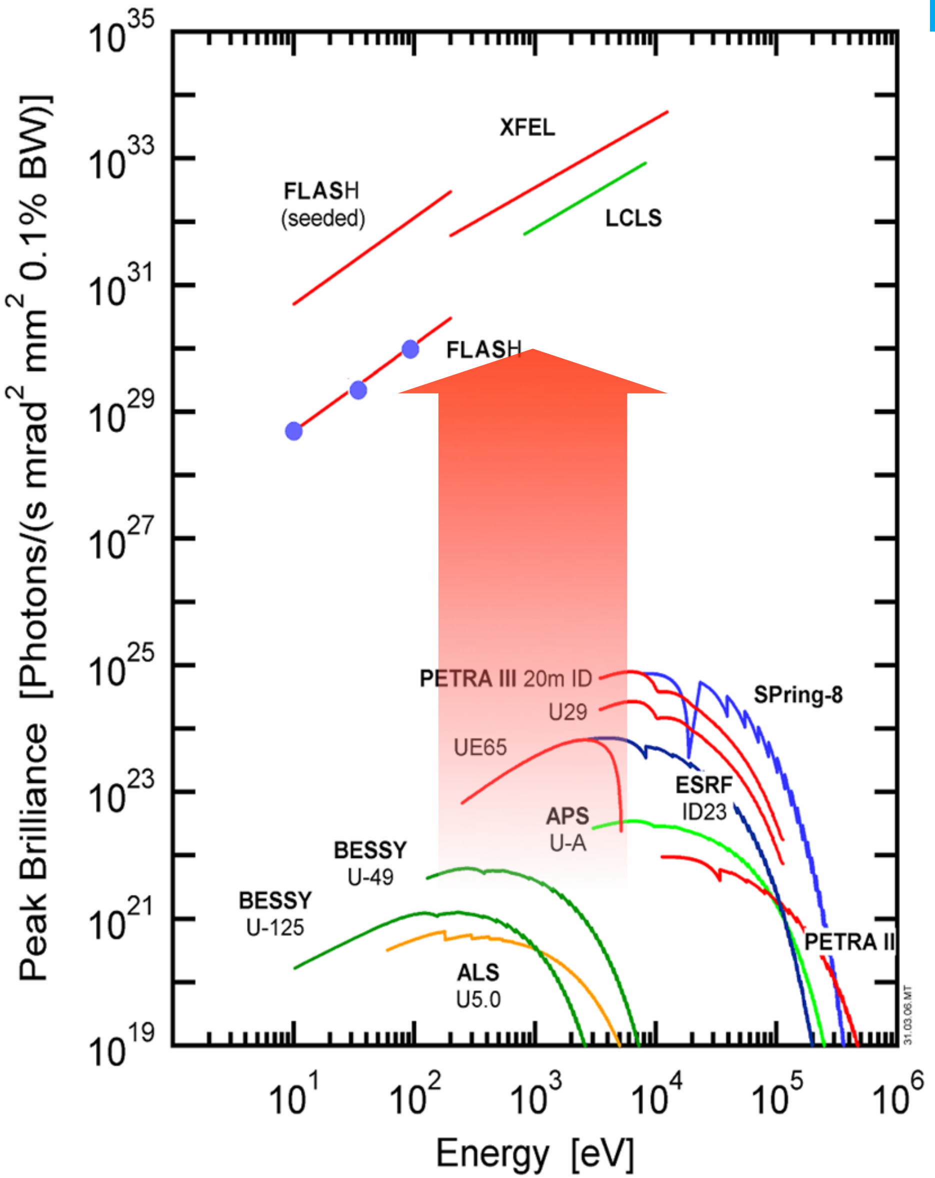
X-ray sources have developed at a staggering pace since their discovery in 1895



S. Bajt, 2011 International Workshop on EUV and Soft X-ray Source, November 7-10, 2011, Dublin, Ireland

XFELs provide intense, short duration, and coherent X-ray pulses

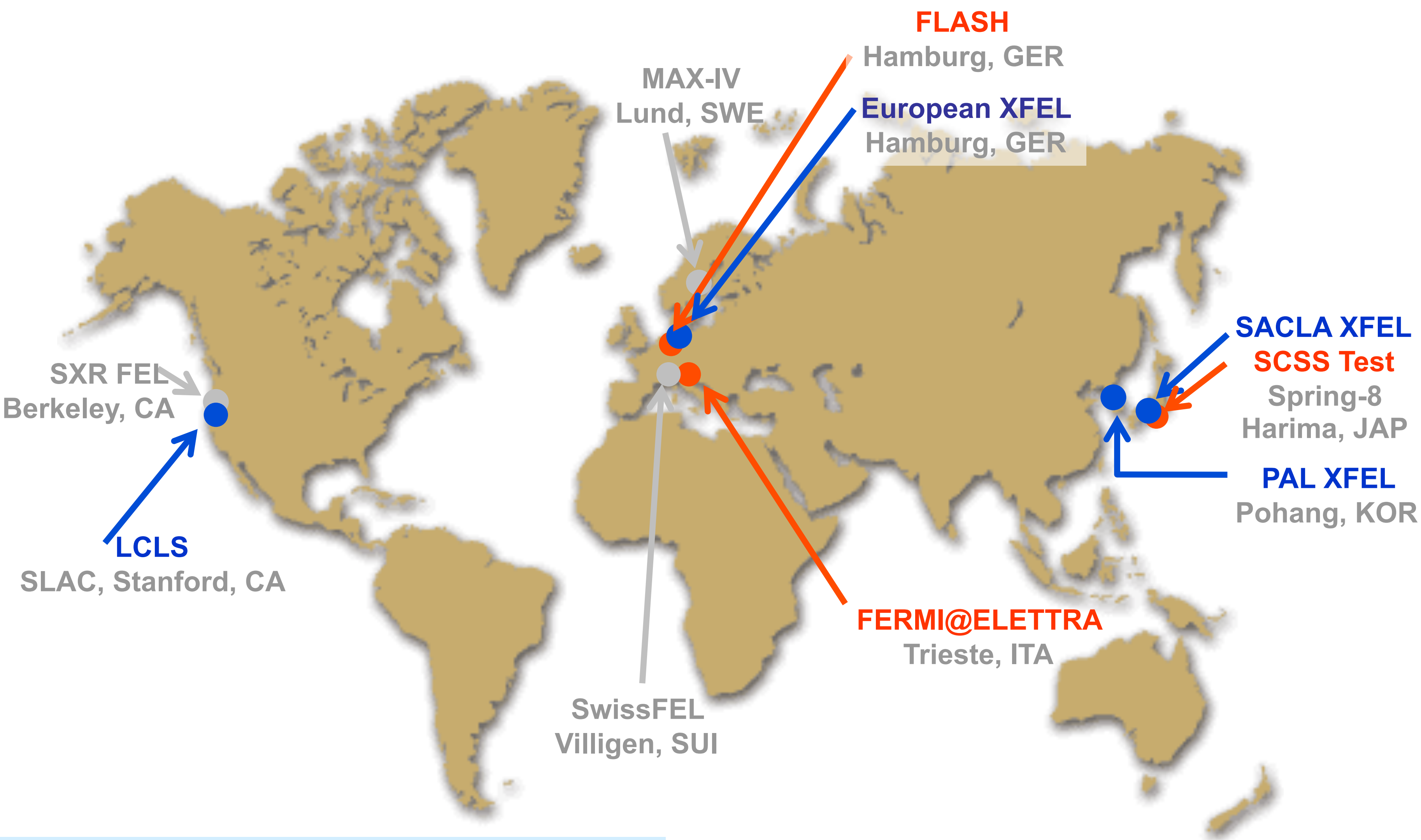
Photons per phase space volume and bandwidth element



$$\sim 10^9 \begin{cases} 10^6 \text{ by FEL gain} \\ 10^3 \text{ by } e^- \text{ quality} \end{cases}$$

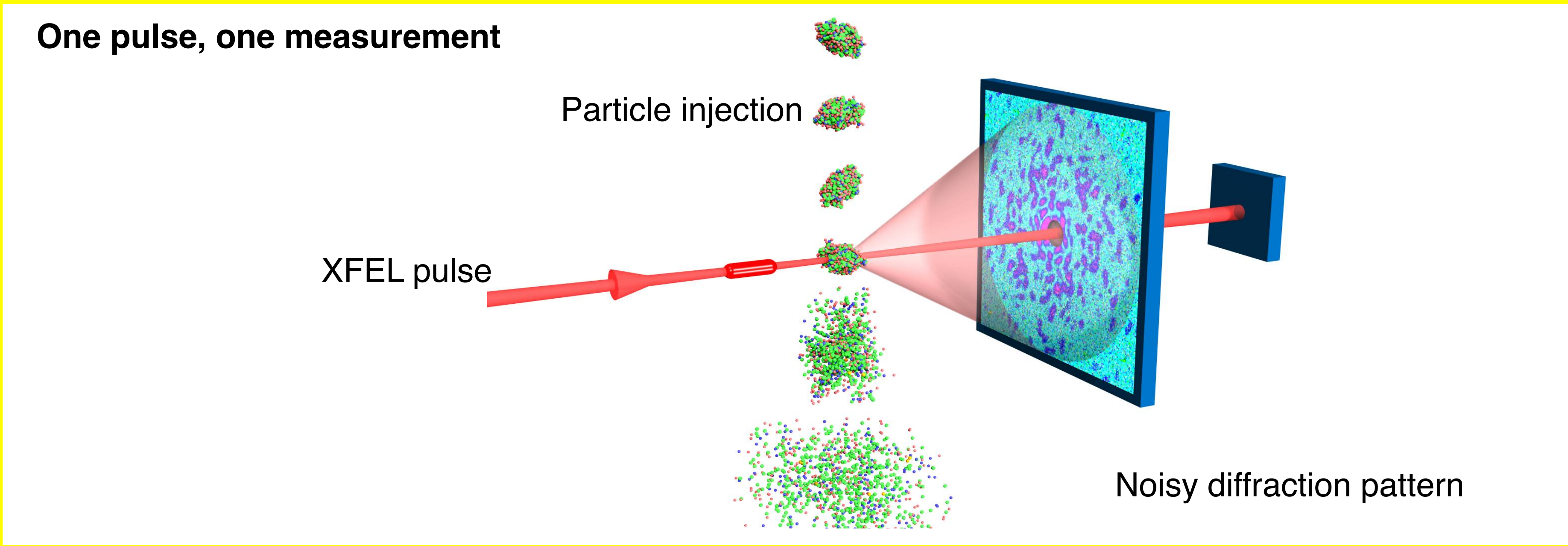
S. Bajt, 2011 International Workshop on EUV and Soft X-ray Source, November 7-10, 2011, Dublin, Ireland

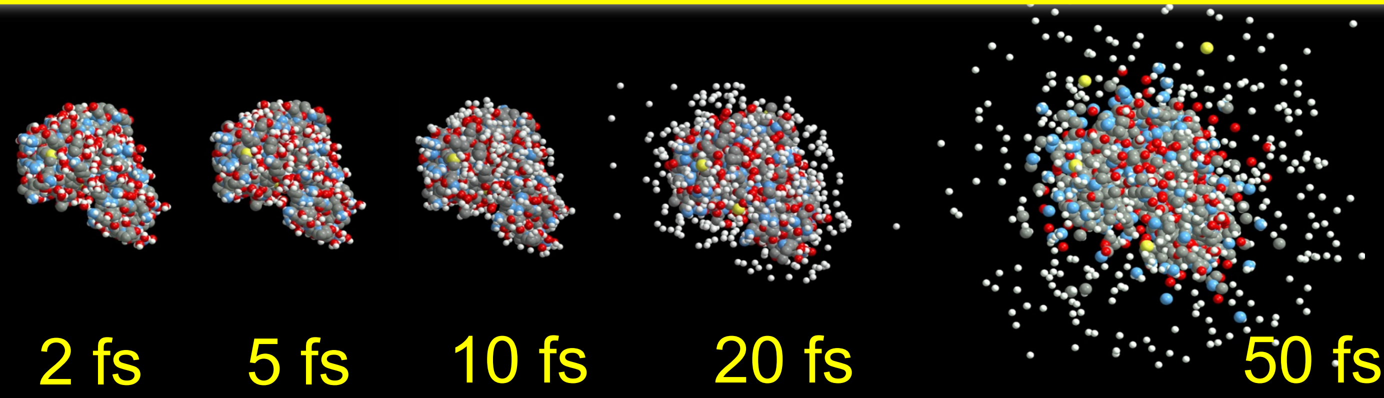
Soft/hard X-ray FELs worldwide



Courtesy: Thomas Tschentscher (European XFEL)

XFELs may enable atomic-resolution imaging of biological macromolecules



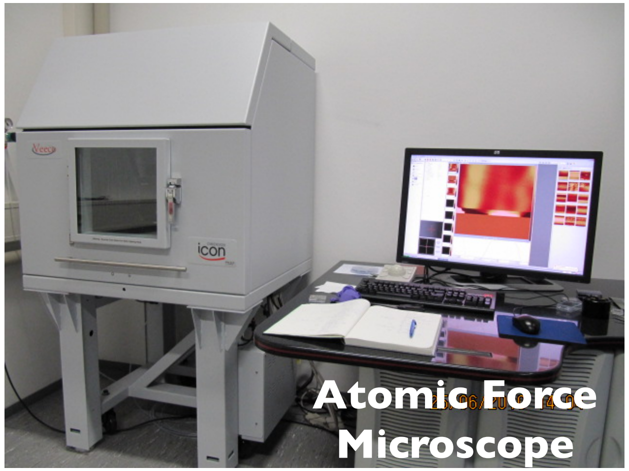


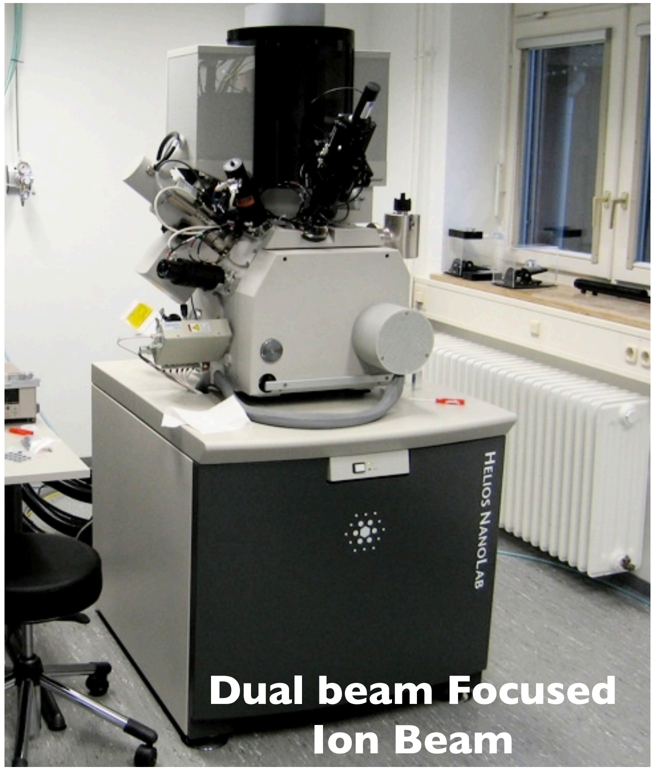
R. Neutze, R. Wouts, D. van der Spoel, E. Weckert, J. Hajdu, Nature **406** (2000)

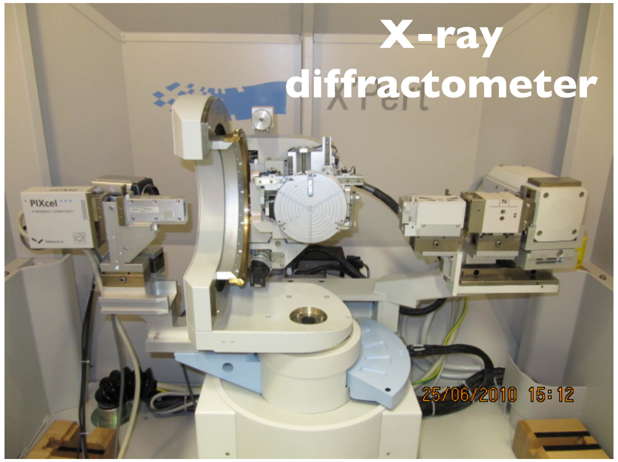
Center for Free-Electron Laser Science (CFEL)

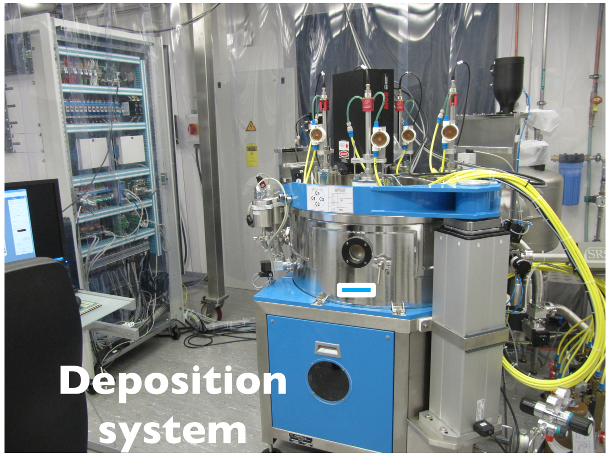
Coherent Imaging & Scattering
Condensed Matter Structural Dynamics
Atomic Resolution Structural Dynamics
Theory
Laser Science
Max Planck Advanced Study Group
U Hamburg Advanced Study Group

At DESY we established a new multilayer optics laboratory



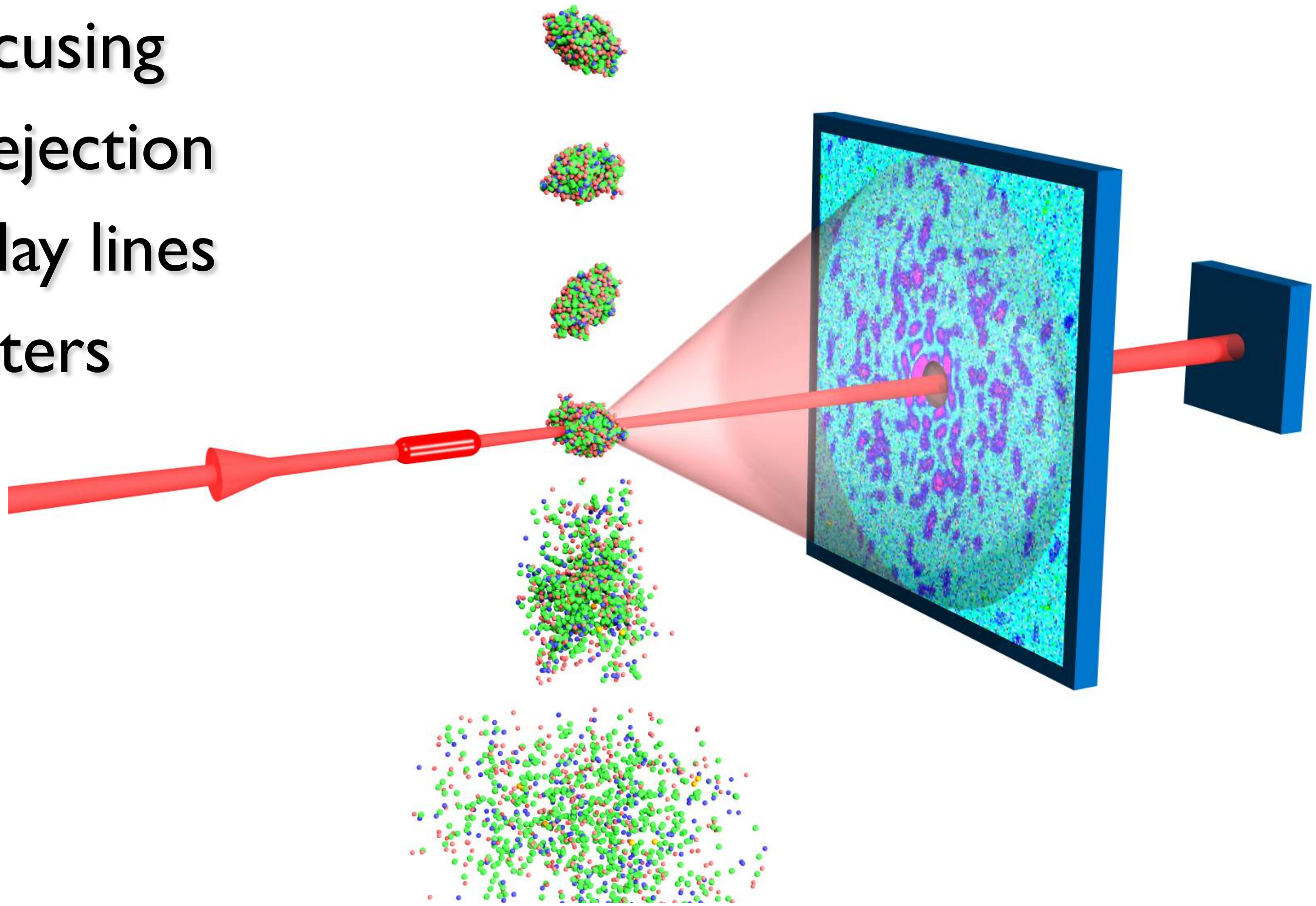






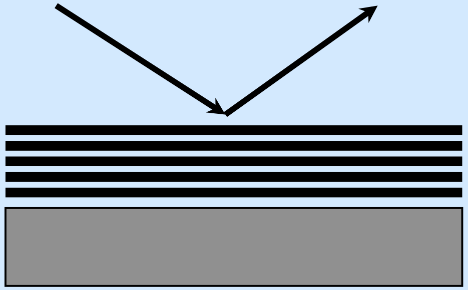
Some examples of multilayer-based optics and optical elements with FEL sources

– High-NA focusing
– Harmonic rejection
– Split-and-delay lines
– Interferometers



First EUV-FEL experiments with MLs showed that structural information can be obtained before destruction

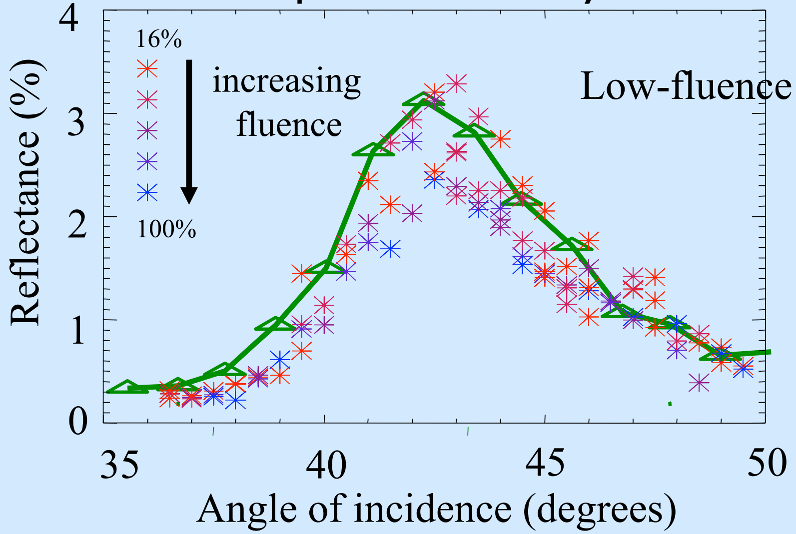
During 30 fs pulse (10^{14} W cm^{-2})
32 nm wavelength



Si/C multilayer

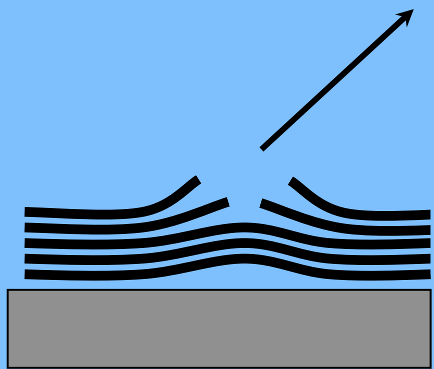
Reflectivity unchanged
Multilayer *d* spacing not changed by more than 0.3 nm

30 fs pulse reflectivity at 32nm

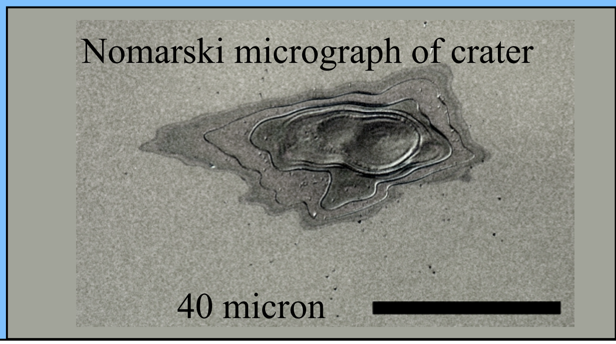


Each point is a new mirror location -- plasma forms and leaves a crater

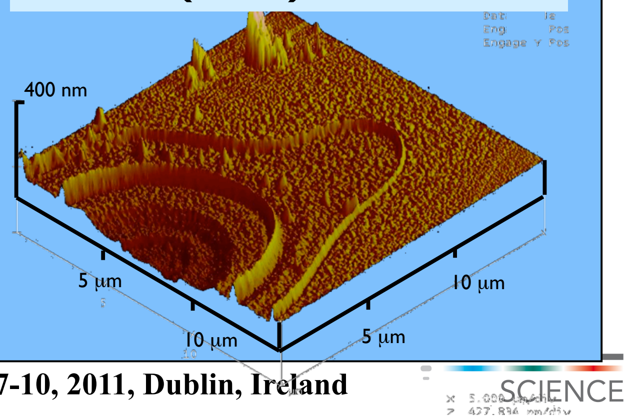
After pulse



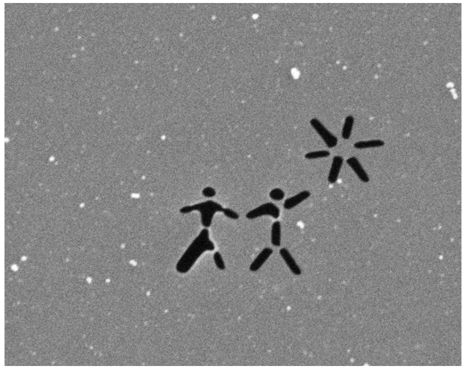
Plasma forms, layers ablate

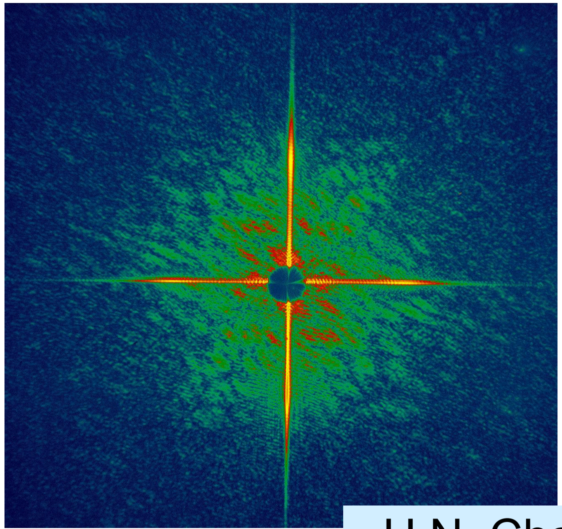


S. Hau-Riege et al., PRL 98 (2007) 145502



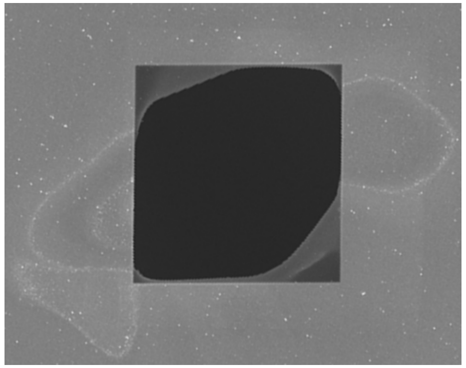
The samples placed in the focused FEL beam get damaged (destroyed)

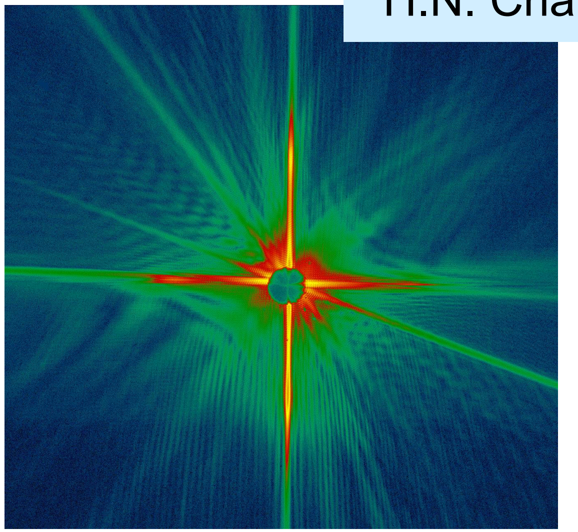




However, x-ray diffraction pattern is collected before destruction.

H.N. Chapman et al., Nat. Phys. 2 (2006) 839





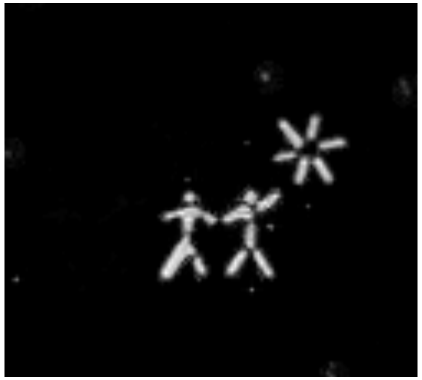
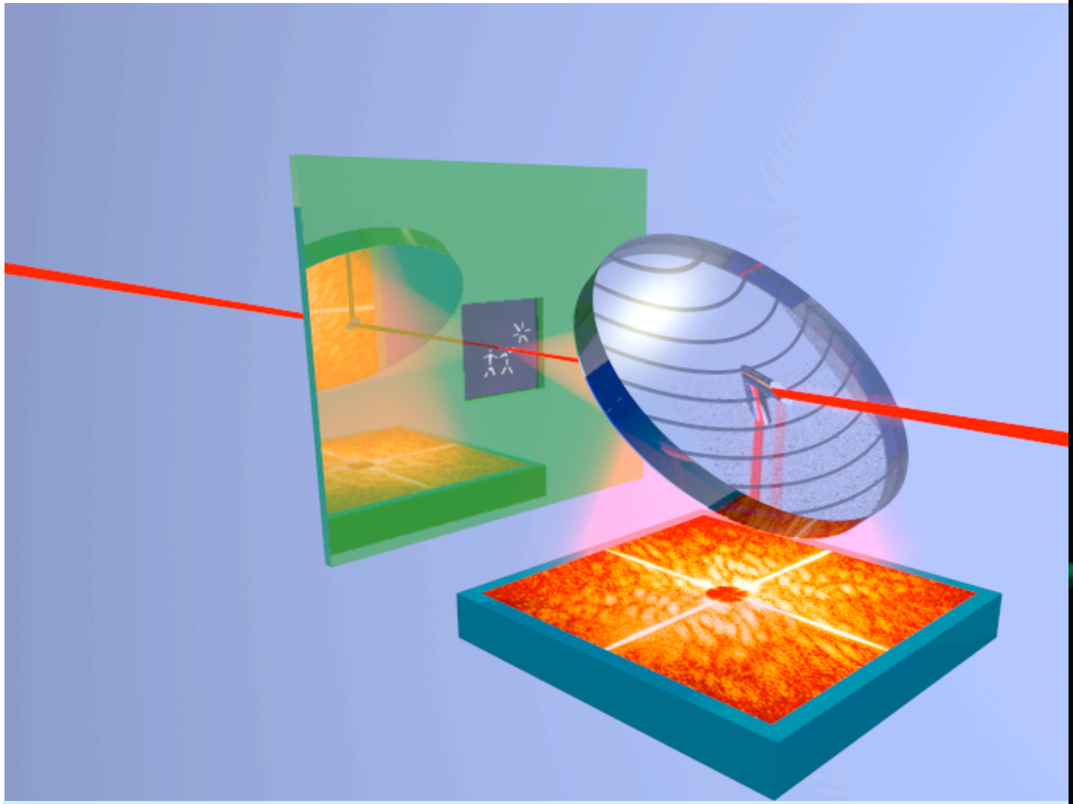


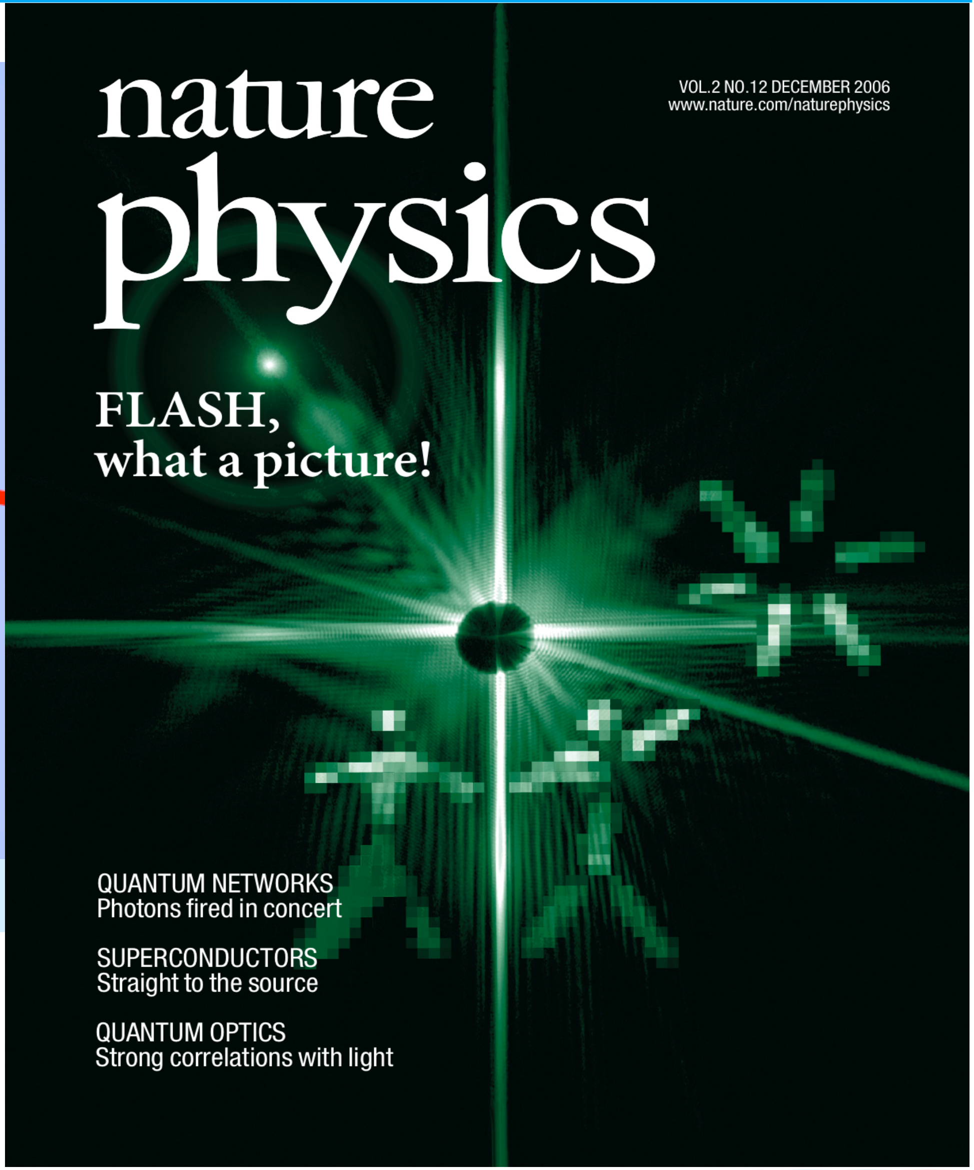
Image reconstructed from a single X-ray diffraction pattern.

The sample was heated to 60,000 K by the FEL pulse

Our multilayer mirrors enabled new science at FLASH

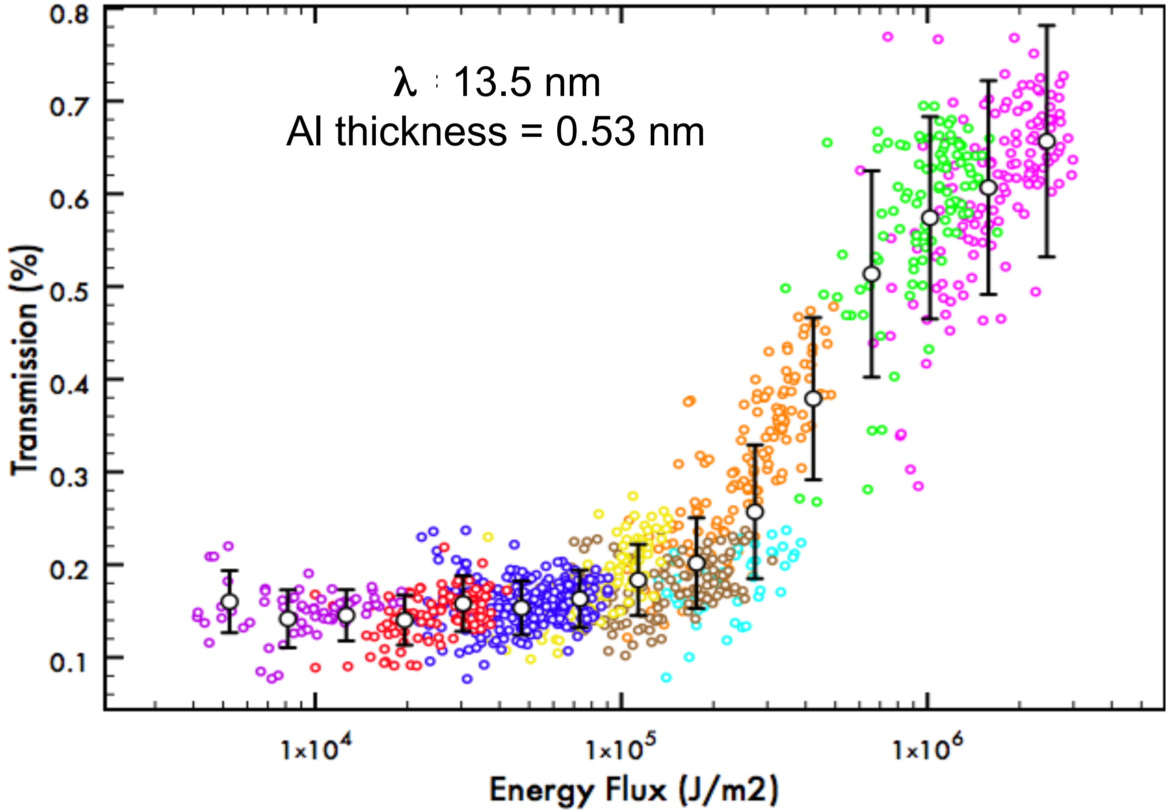


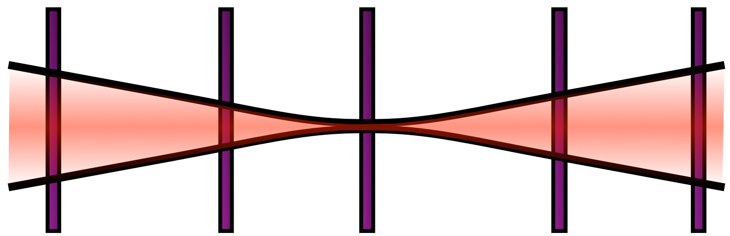
H.N. Chapman et al., Nat. Phys. 2 (2006) 839



First demonstration of ultrafast coherent X-ray diffraction

Tighter focus (higher intensity beam) enables new science



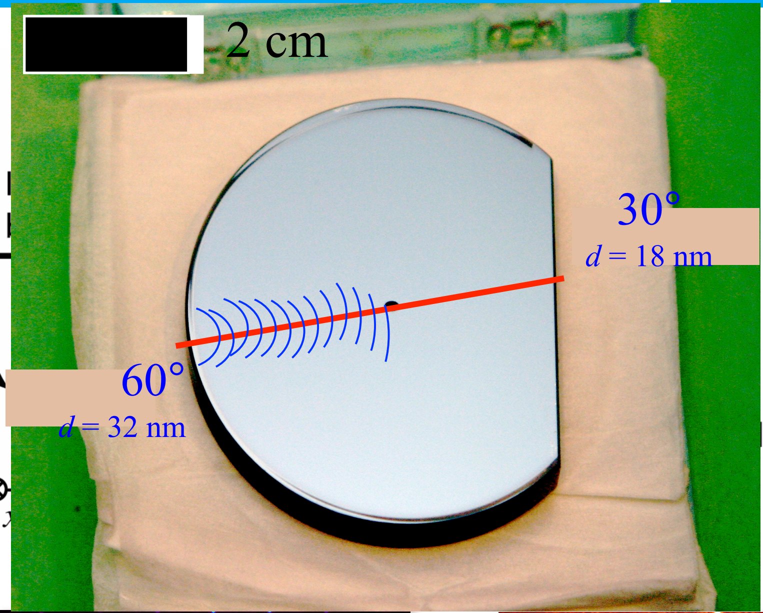


Transmission was measured in different focal spot conditions – simple way of varying the intensity

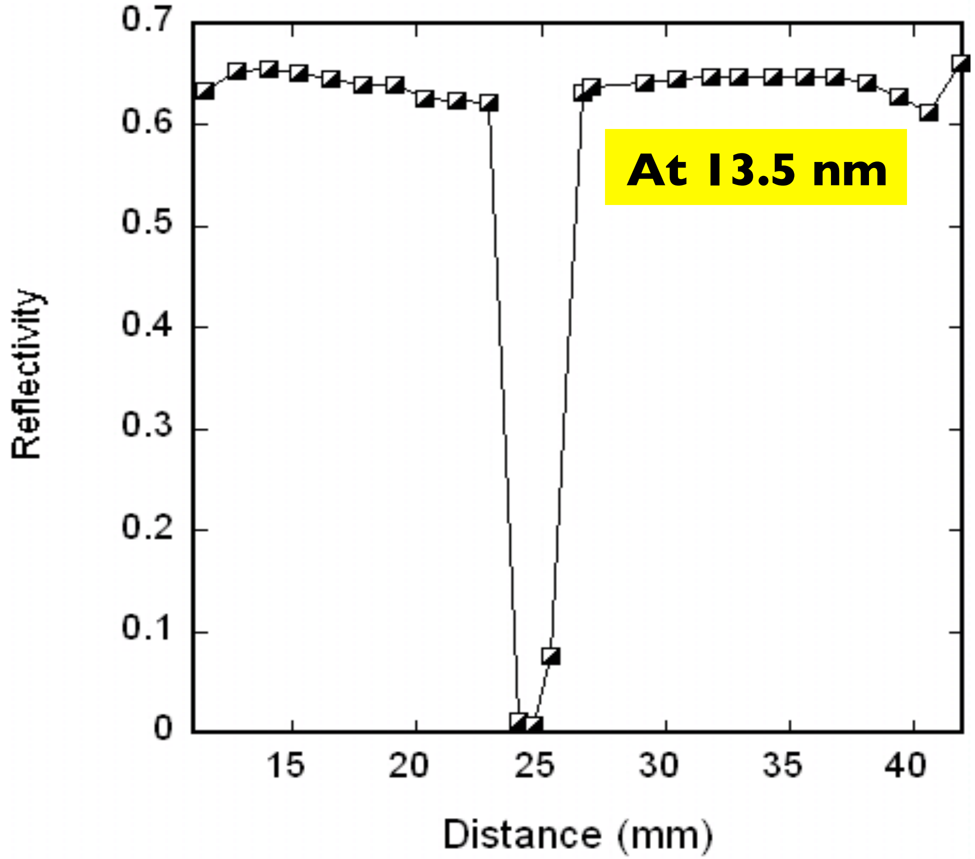
Under intense FLASH beam the transmission of a thin Al foil changes dramatically.

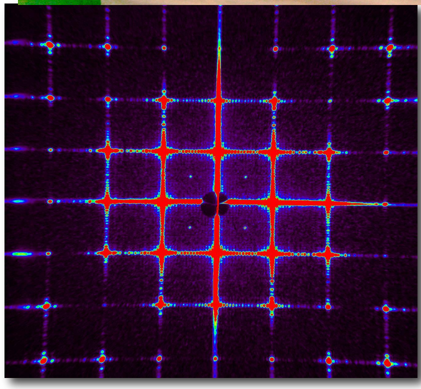
B. Nagler et al., Nature Phys. 5, 693 (2009)

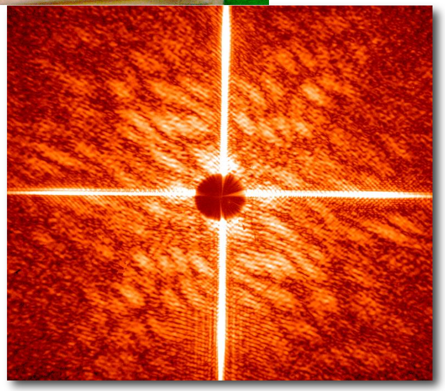
Mirrors for FEL experiments require lateral thickness gradients with atomic precision and stress control



Such mirrors were developed for wavelengths between 4.5 nm and 32 nm.





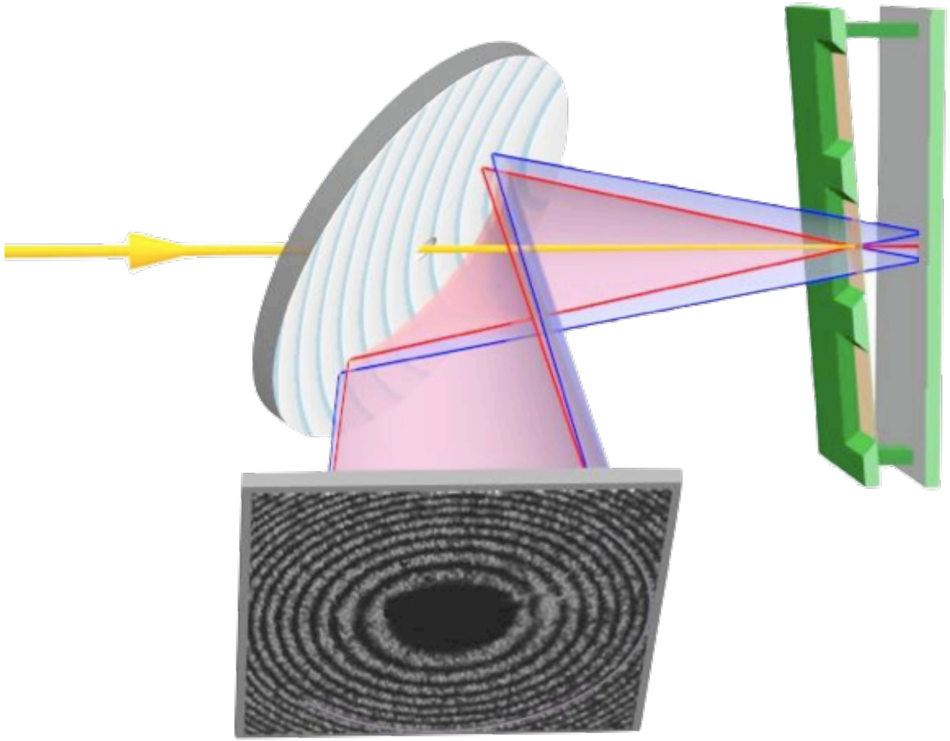


Multilayer reflectivity is uniform across the 30°to 60°gradient

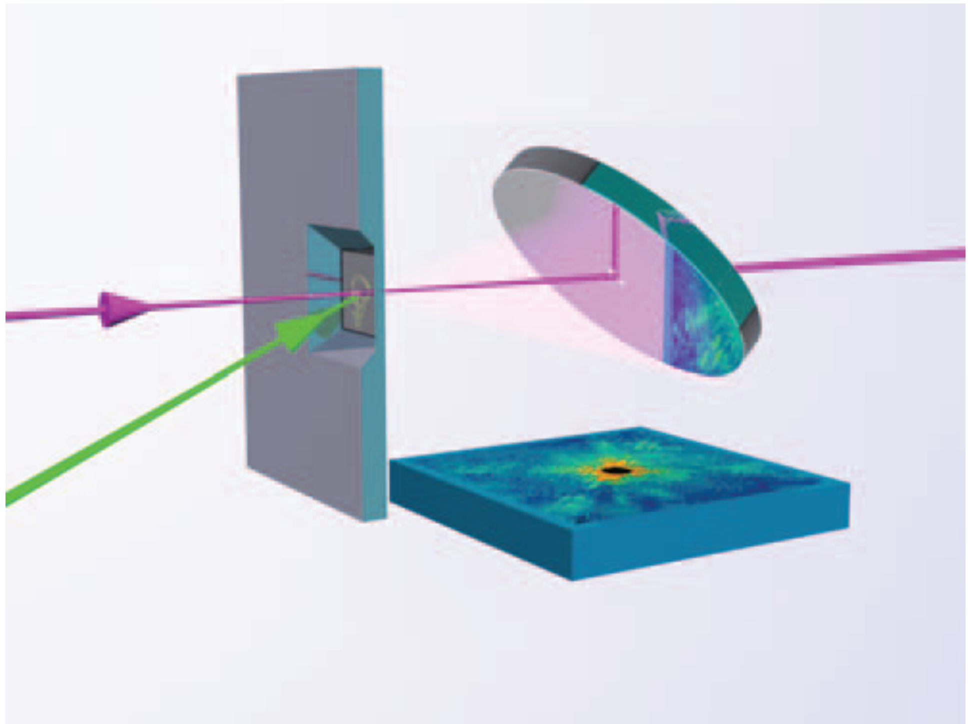
"Soft edge" prevents any scatter from the hole

S. Bajt et al., Appl. Opt. 47, 1673 (2008)

The same type of optic was used at different wavelengths, geometries and XFEL experiments



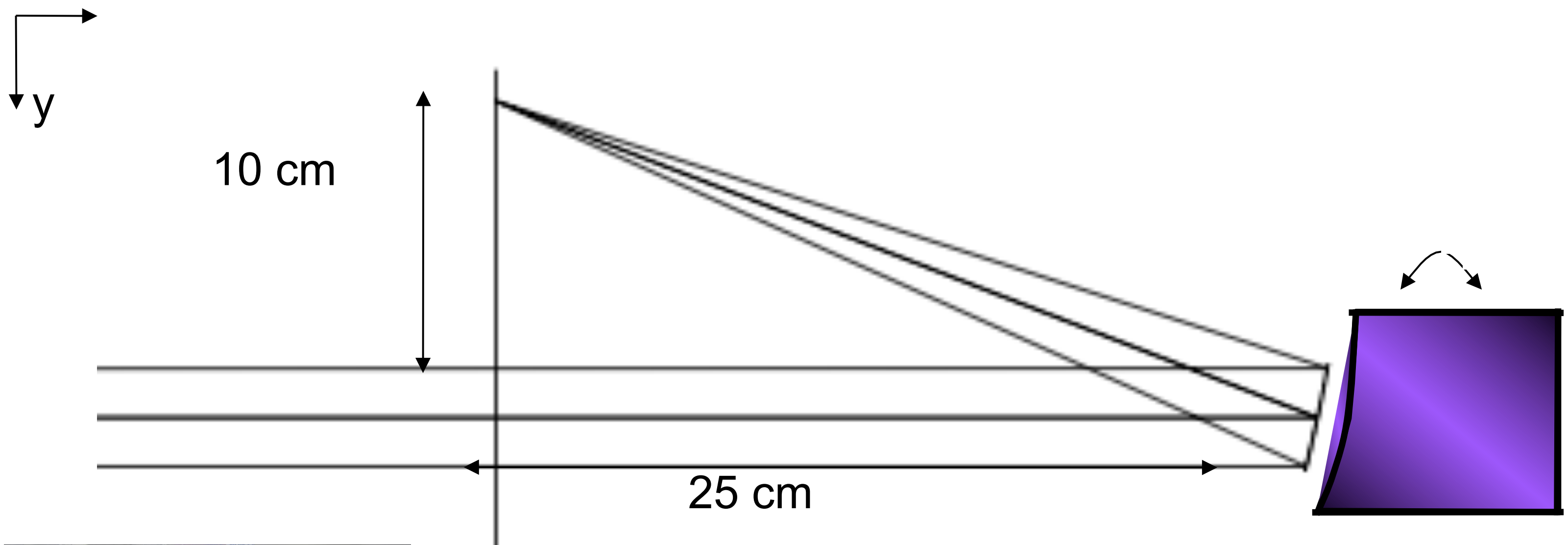
H. N. Chapman et al, Nature 448, 676 (2007)

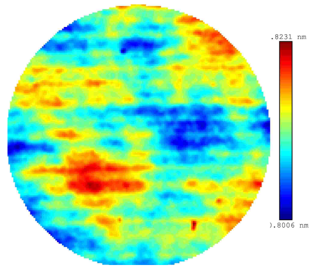


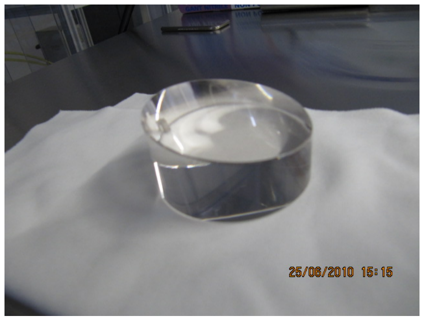
A. Barty et al., Nature Photon. 2, 415 (2008)

S. Bajt et al., Appl. Opt. 47, 1673 (2008)

Off-axis multilayer coated optics focused FLASH beam to submicron dimension





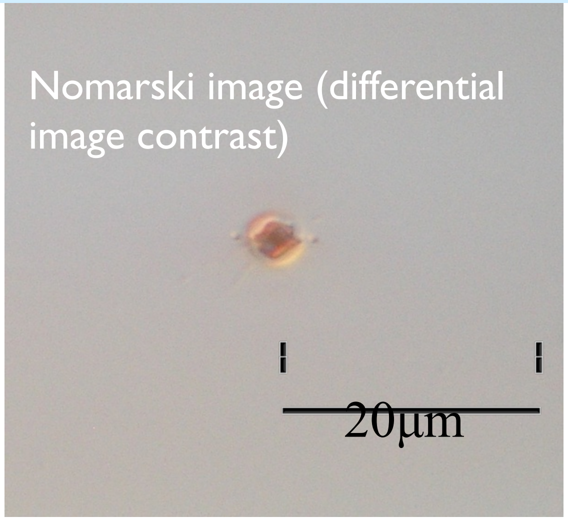


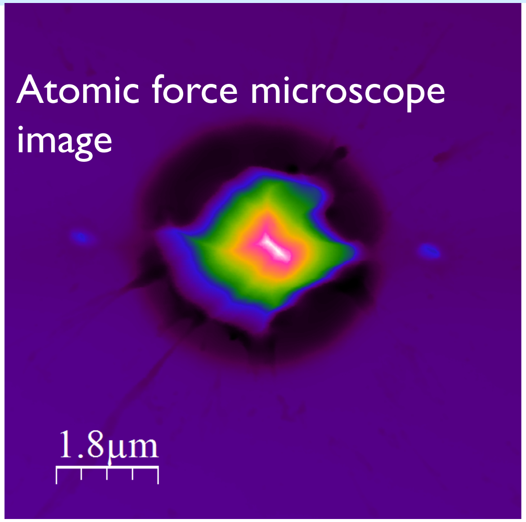
- Focal spot <1 μm
- Intensity 40 μJ / (40 fs $(10^{-4}$ cm$)^2$)
  ~ 10^{17} W/cm^2

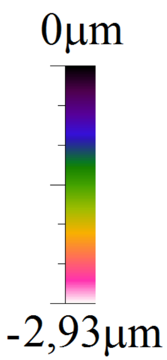
A. Nelson et al., Opt. Exp. 17, 18271 (2009)
S. Bajt et al., SPIE 7361 (2009)

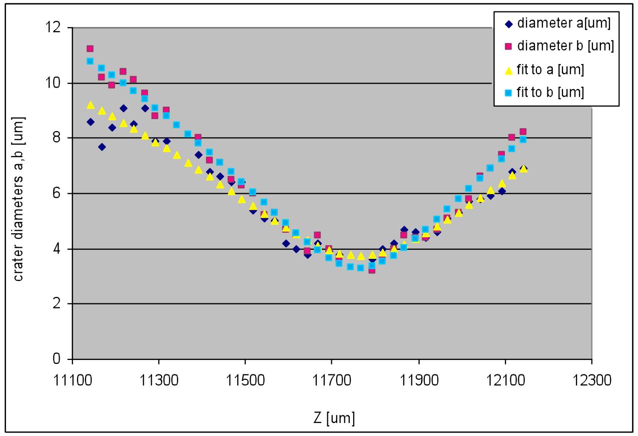
PMMA exposed samples – focus characterization based on Nomarski images and AFM profiles of the craters

Courtesy: T. Burian, V. Hájková, J. Chalupský (IOP, Prague)

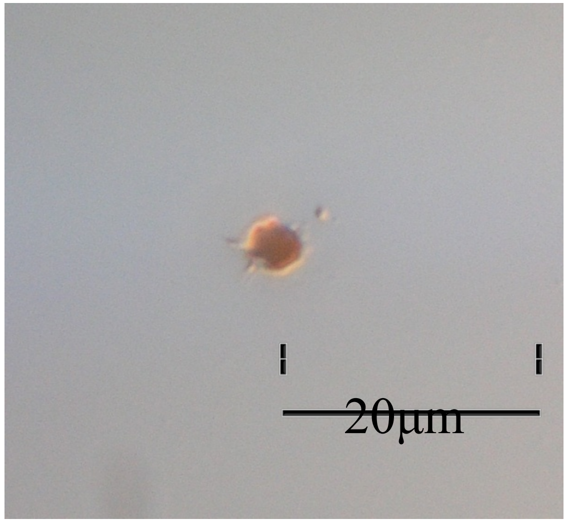


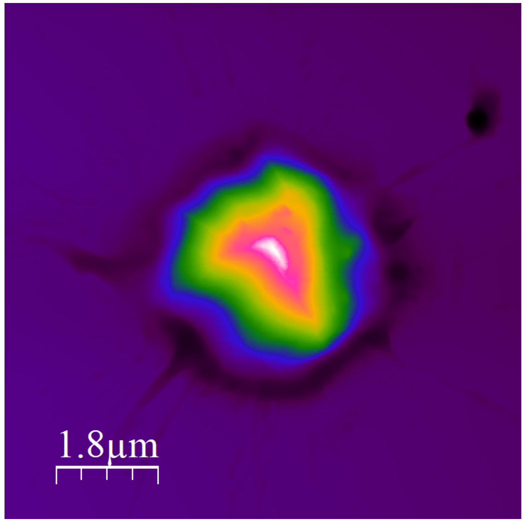


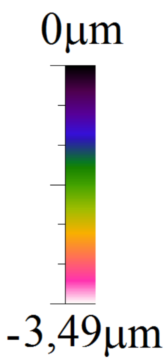




128 μ m out of focus

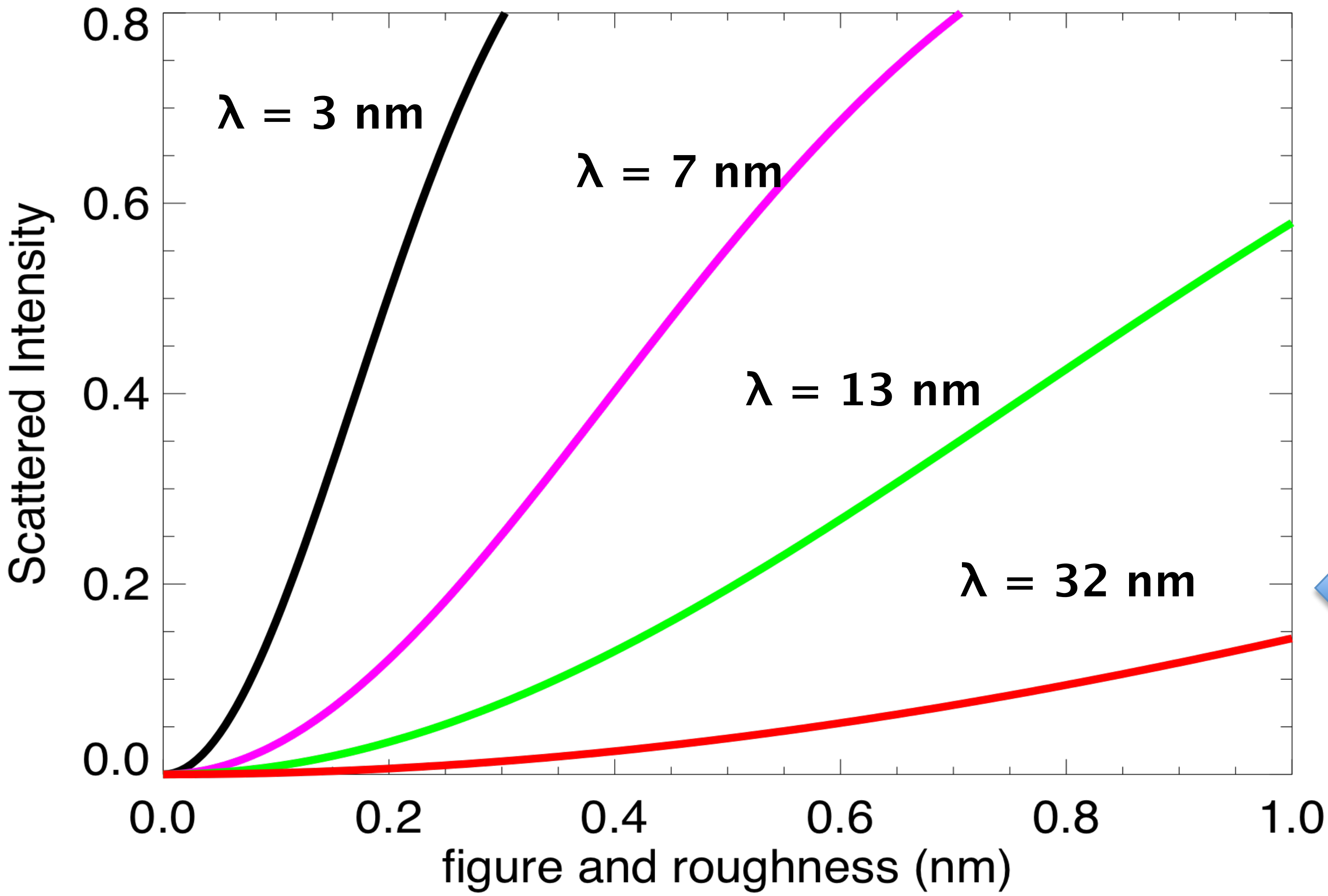






228 μ m out of focus

Scattering increases dramatically for shorter wavelengths



Marachel

S. Bajt et al., SPIE 7361 (2009)

Multilayers for 6.x nm wavelength

Considerations:

>Reflectivity, temporal and thermal stability, stress, how easy to work with, availability and price

Candidates:

Normal incidence: 0 to 5 deg off normal; Wavelength: 6 to 7 nm (Source: http://henke.lbl.gov/optical_constants)

Ru/B4C (20% at 6.8 nm, N= 150, J. Korthright)

Cr/C (18.9% at 6.42 nm, N = 150, H. Takenaka)

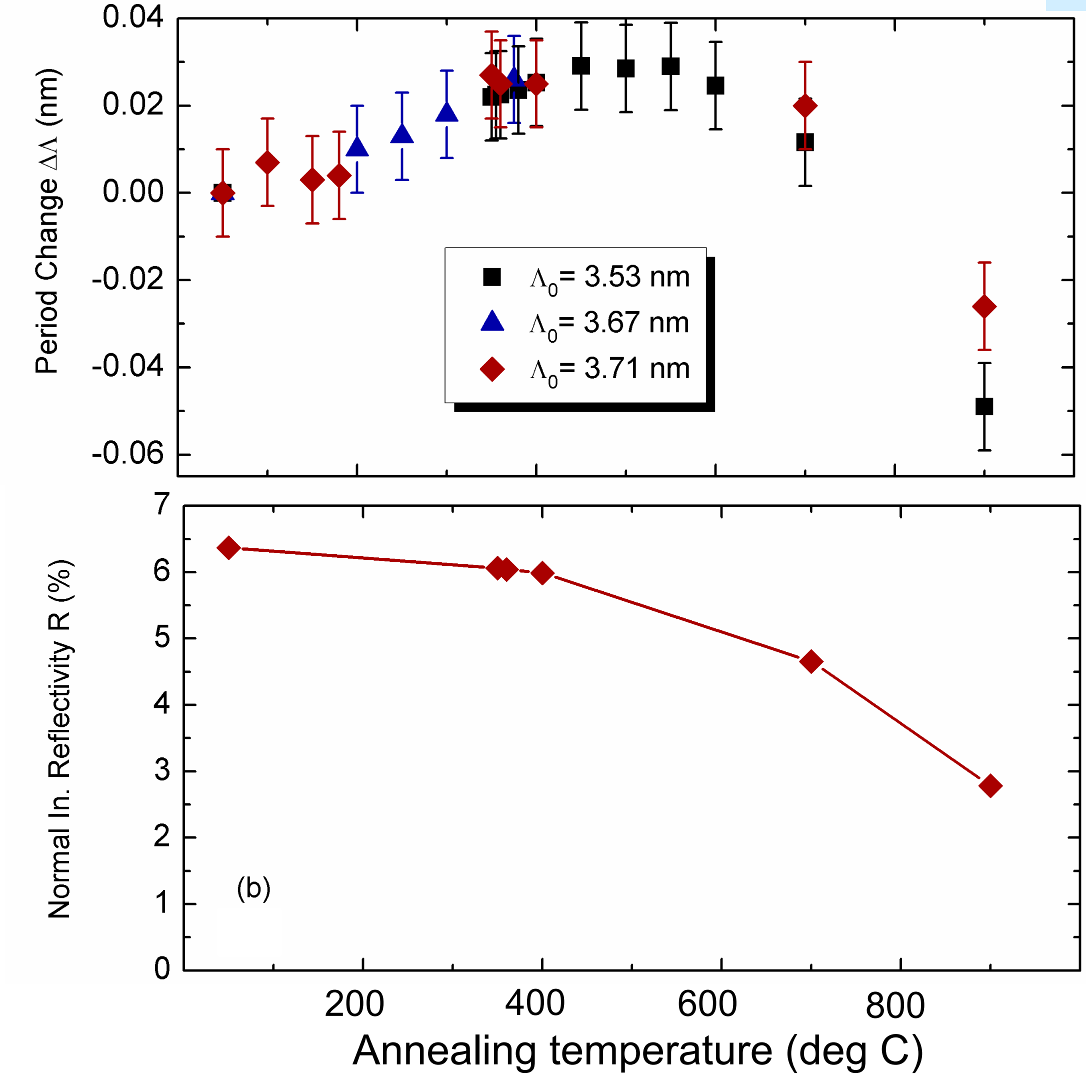
FeCrNi/B4C (16% at 6.8 nm, N = 100, D. Stearns and S. Vernon)

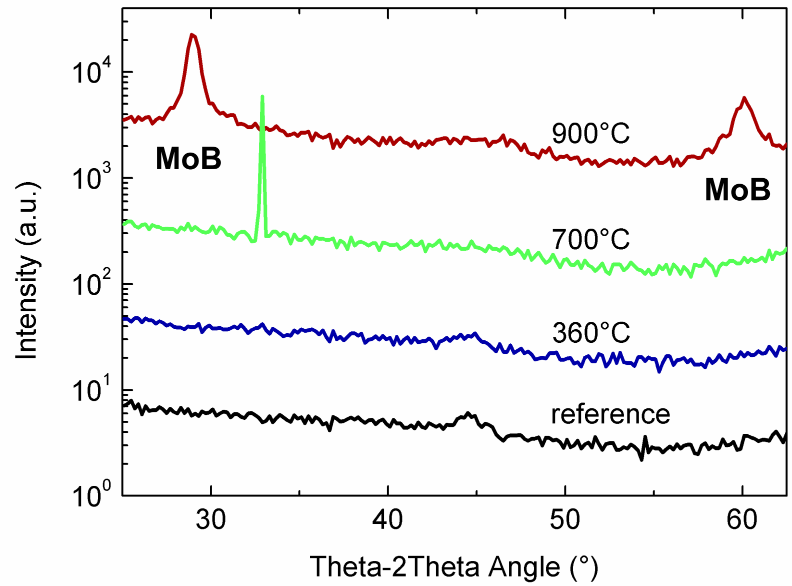
>La/B_4C, LaN/B_4C, LaN/B, La_2O_3/B_4C

>Mo/B, Mo/B_4C

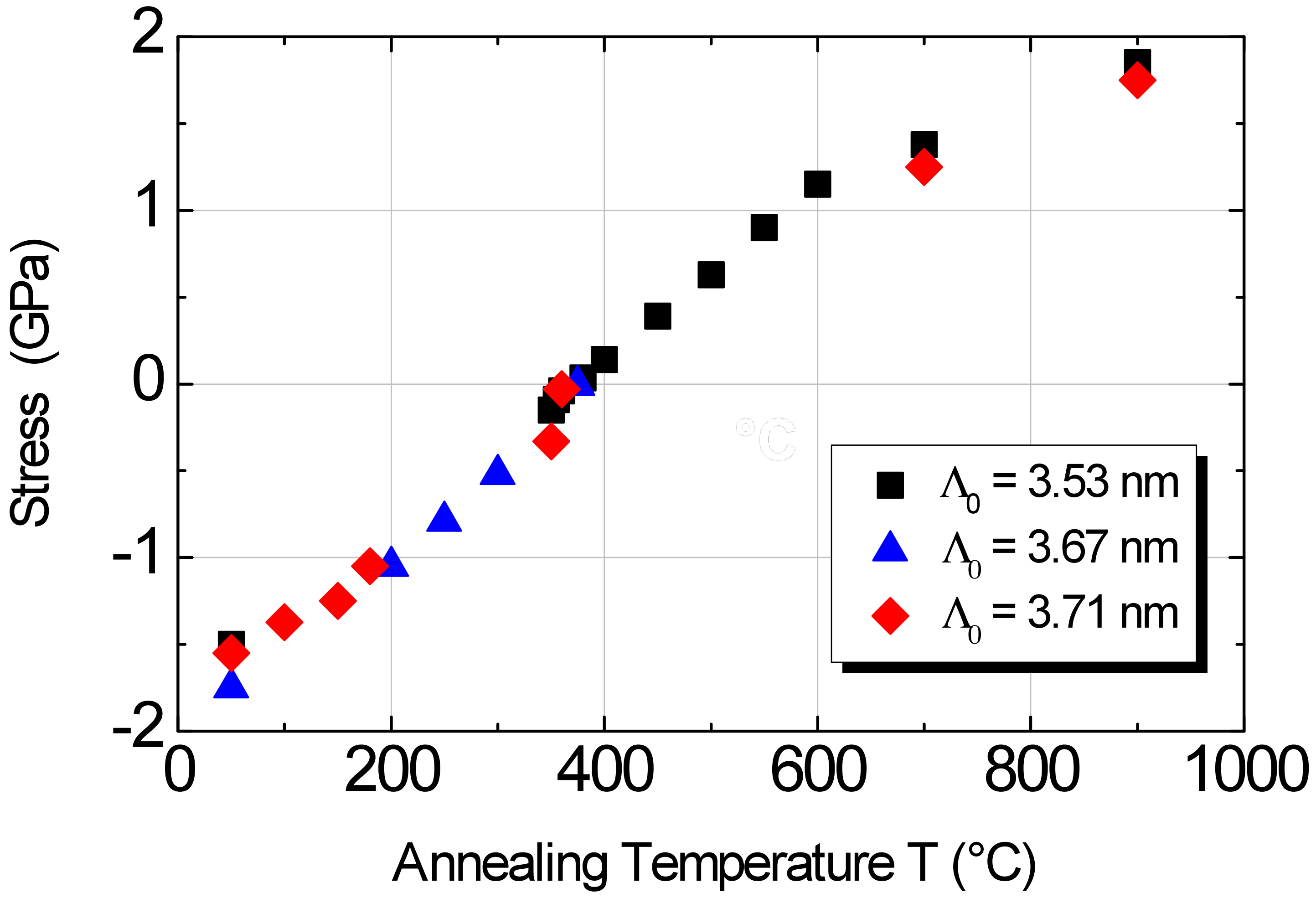
We studied stress and thermal stability of Mo/B_4C MLs (λ=6.8 nm) as function of temperature

M. Barthelmess and S. Bajt, SPIE 8077-37 (2011)



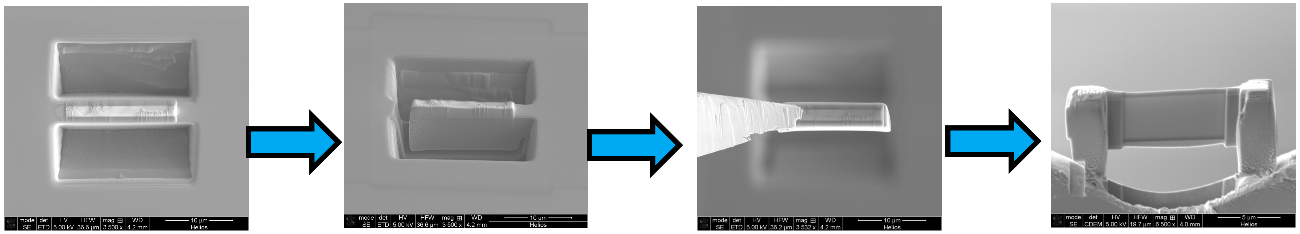


One way to reduce stress is to anneal Mo/B_4C MLs at ~370 deg C



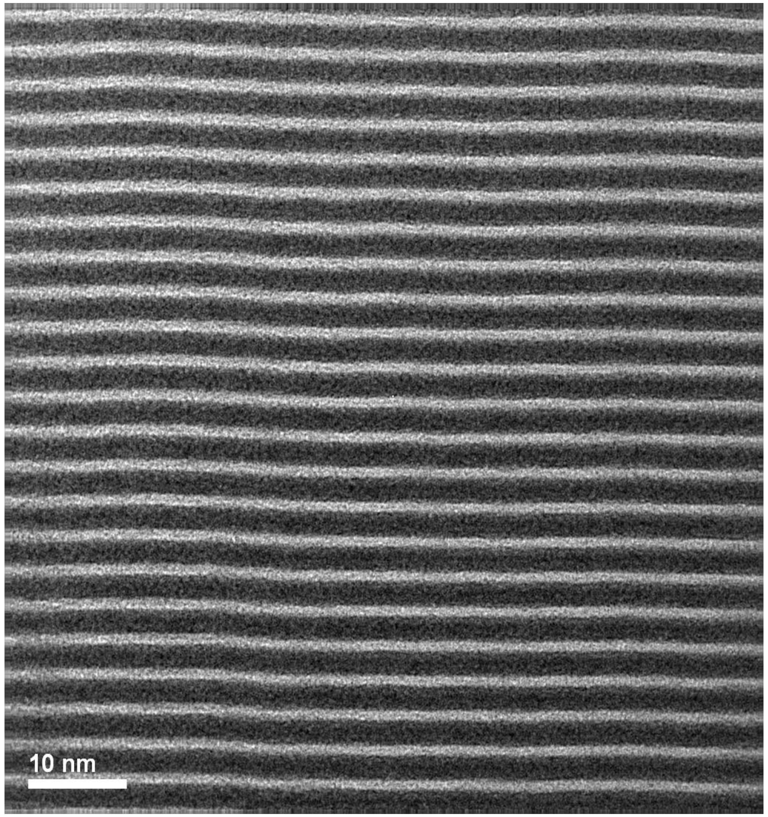
M. Barthelmess and S. Bajt, Appl. Opt. 50, 1610 (2011)

Mo/B_4C ML is thermally stable up to 600 deg C

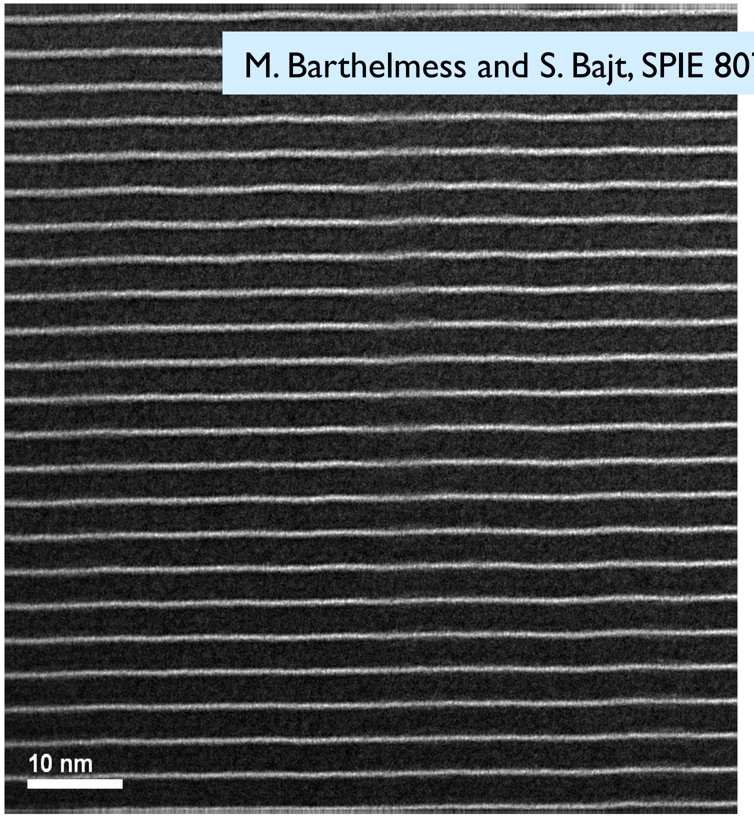


TEM sample prepared by FIB

M. Barthelmess and S. Bajt, SPIE 8077-37 (2011)

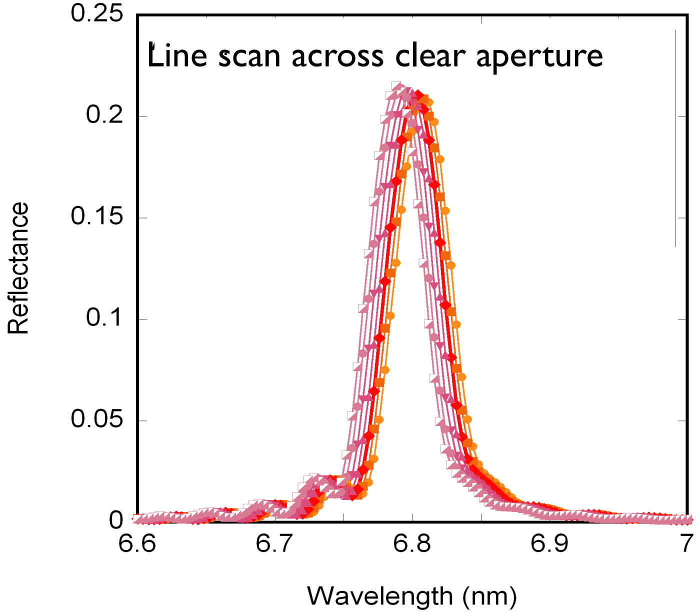


as-deposited state

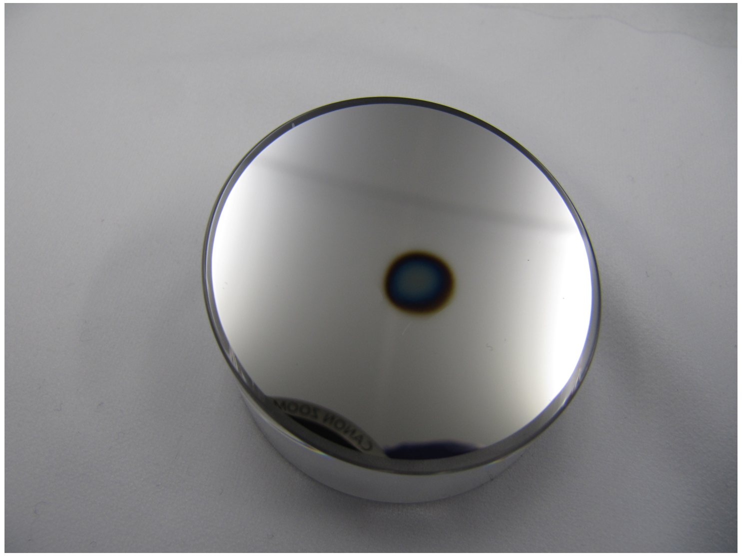


after 1h at 600 deg C

Our normal incidence off-axis optic focused 6.8 nm FLASH beam to sub-micron spot



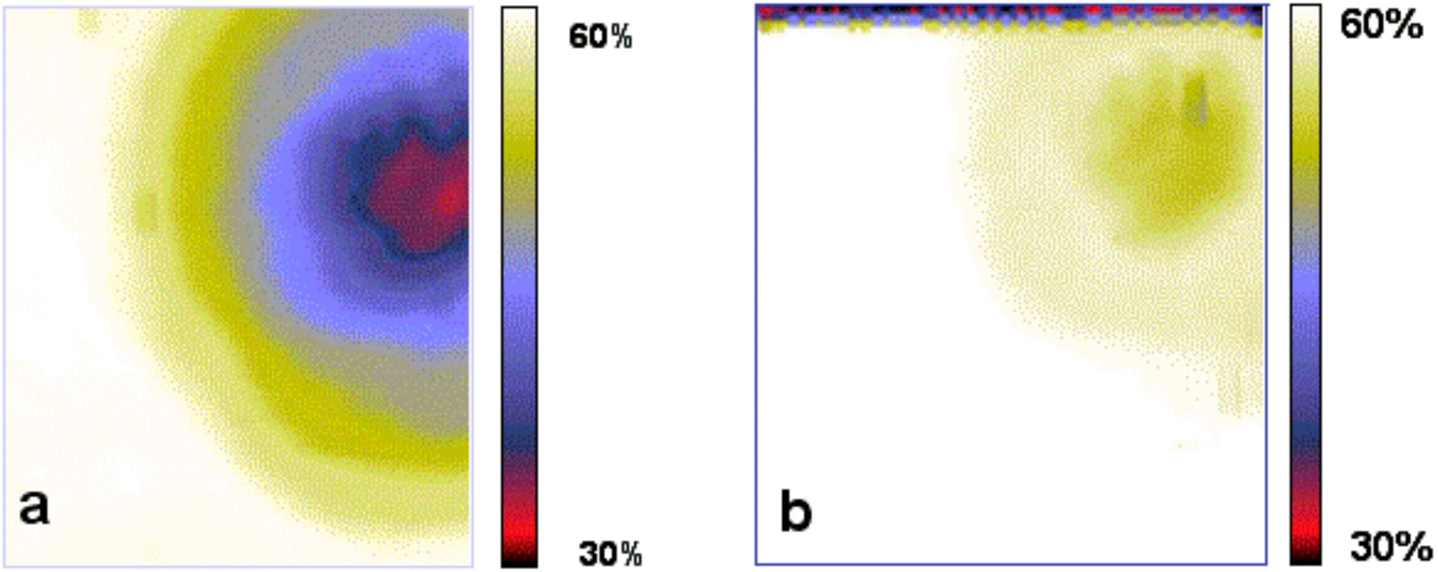
- As-deposited mirror
- Uniform reflectivity
- Uniform wavelength



- Contaminated mirror
- Reduced, non-uniform reflectivity
- Uniform wavelength

Methods to remove surface contamination from carbon containing MLs are being explored

Removing contamination from Mo/Si ML coated off-axis parabola
(S. Bajt et al., SPIE 7361 (2009))



Removing contamination from Mo/B_4C ML coated off-axis parabola is more challenging
(Similar to removing carbon from B_4C coated LCLS mirrors
R. Soufli et al., SPIE 8077 (2011))

Summary

- XFELs have stringent optics requirements, since experiments need to use entire FEL output on every pulse.
- MLs match the intrinsic bandwidth of FEL sources and increase reflectivity and angular ranges
- Novel X-ray optics can be used to manipulate the phase space of X-rays
- Many FELs require lots of ML optics

Acknowledgements

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F. Schäfers (HZB, BESSY II, Germany)

F. Siewert (HZB, Bessy II, Germany)

S. Nannarone, N. Mahne, A. Giglia (Elettra, Italy)

* (now at European XFEL)